Optical Materials 34 (2011) 457–460

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Applications and performance of high power lasers and in the battlefield

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ARTICLE INFO

Article history:
Received 14 March 2011
Accepted 7 April 2011
Available online 31 May 2011

Keywords:
Laser weapon
Chemical lasers
Solid state laser
ABL
Fiber lasers
Disk laser

ABSTRACT

This paper reviews the status and applications of a defensive weapon based on high power lasers, in the battlefield. Laser weapon is a novel concept which utilizes high power laser beam to traverse the distance into incoming objects at a *speed of light,* and then, destroy or disable it. Various types of lasers and configurations will be discussed in this review including gas lasers, solid state lasers, fiber lasers and the free-electron laser. We will discuss various configurations such as airborne laser (ABL), diode pumped crystals and disk lasers as well as heat-capacity lasers. Recent applications of ultrafast solid state lasers for non-lethal or low collateral damage applications will be presented.

1. Introduction

Laser weapon is currently considered as tactical as well as strategic beam weapons, and is considered as a part of a general layered defense system against ballistic missiles and short-range rockets. This paper is an extended and updated version of the two recent papers presented and published recently [1,2]. The laser weapon is a kind of weapon that can disable or destroy military targets or incoming objects, by approaching the target at a *speed of light*, and this is attractive against short-rage rockets and mortars. Laser weapon, unlike kinetic is effective in principle, at long or short distances, owing to beam's unique characteristics such as narrow bandwidth, high brightness, coherent both in time and space. The laser beam, aimed on a small area spot at the rocket's skin is converted into a large amount of heat, following by a temperature increase and finally-catastrophic failure by material ablation or melt.

The usefulness of laser light as a weapon has been studied for decades but only in recent years became feasible owing to advances in solid state laser materials and thermal management technologies. There are two types of lasers based on the active lasing media that are being used: gas lasers and solid state lasers, including fiber lasers. All these types of lasers will be discussed below.

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doi:10.1016/j.optmat.2011.04.005

2. Gas lasers

There are two types of gas lasers.

2.1. Tactical high energy laser (THEL)

This type of laser is based on HF/DF (2.6–3.3/3.5–4.2 m) chemical laser, which is based on a technological demonstrator termed also as MIRACL – Mid Infrared Advanced Chemical Laser, based on DF laser (3.8 m), with output power in the range of about 1 MW. The MIRACL was the precursor of the *Nautilus* DF-based laser system, developed jointly by US and Israel. An advanced version of ground-based THEL, the Skyguard, was introduced in 2006. The basic reaction of the HF/DF chemical laser is a "*chain reaction*", between atomic fluorine (generated by electrical discharge from F_2, NF_3, SF_6, etc.) and molecular hydrogen (or deuterium), or other sources such as H_2O_2 or C_2H_4, namely:

$$F + H_2 \rightarrow HF^{*} + H \quad (\text{cold reaction, exothermic, } 31.6\ \text{kcal/mole}) \tag{1}$$

$$H + F_2 \rightarrow HF^{*} + F \quad (\text{hot reaction, exothermic, } 98\ \text{kcal/mole}) \tag{2}$$

The cycle (2) is repeated by the atomic fluorine. The reaction is initiated by electrical discharge which dissociates the molecular fluorine into reactive fluorine atoms. Our team at NRCN obtained atmospheric-pressure operation of chemical lasers (such as HF) by using various preionization technologies. In our research, we found that using a novel design of plasma-cathode preionized HF laser

yielded, for the first time, an efficient room temperature atmospheric pressure chemical laser.

The vibrational population inversion is achieved by the heat generated in the chemical reaction, and the emission wavelength is in the range of 2.7–4.2 m. The mobile version of this laser (MTHEL – Mobile Tactical High Energy Laser) can be ground based with 100 kW output power (or more) needed to destroy short range rockets or artillery shells, or airborne by C-130, C-17 or C-5 airplanes. The MIRACL version of this DF chemical laser is a megawatt-class laser, with beam dimensions of 14×14 cm, and it operated successfully for 70 s. All these lasers are equipped with advanced target acquisition system as well as Pointer Tracker Subsystem (PTS).

2.2. Airborne laser (ABL)

This Chemical Oxygen–Iodine Laser (COIL) is a megawatt-class laser, emitting at 1.315 m, is a strategic weapon. The population inversion is achieved by a chemical reaction between excited *singlet* molecular oxygen and molecular iodine, leading energy transfer between *singlet oxygen* and atomic iodine and to population inversion in the excited state. The laser operates, similarly to other chemical lasers, at low pressure and fast flow conditions, so heat removal from the lasing medium is easier relatively to high power solid state lasers. This reaction is enhanced at lower temperatures towards the production of more excited iodine atoms, therefore supersonic expansion nozzles to cool the reactants is used. It can produce several MW output power, in 20–40 shots, during 300–400 s. The laser is carried on a Boeing 747–400 F freighter aircraft at 40,000 ft., and is named also as YAL-1A. See Fig. 1.

The laser weapon system includes also the BMC4I – battle management, command, control, communications, computers, and intelligence. This laser is intended to destroy the missile before separation of warheads, at the boost phase, at a distance of about 400 km, when the missile is relatively slow and vulnerable to attack. An Advanced Tactical Laser (ATL) version of this laser, mounted to a C-130 aircraft, was recently fired during flight, and it hit a target on the ground, for the first time. In addition to the main laser, the HEL requires target acquisition and tracking system. They are the Active Ranger System (ARS) for primary tracking and prioritizing, The Track Illuminating Laser (TILL) to track and stabilize the laser, and the Beacon Illuminating Laser (BILL) to compensate for atmospheric distortion along the path of the laser beam to the target.

3. Solid state lasers

Solid state lasers (SSL) are presently considered as a future tactical anti-missile, anti-rocket, and anti-mortar laser weapon. Tactical laser weapon based on SSL are used for ultra-precision missions with reduced collateral damage, suitable as a tactical directed energy weapon both in the battlefield and in urban environment. They are based on solids (crystals such as YAG, or crystalline YAG-ceramics) doped with rare earth ions such as Nd^{3+} or Yb^{3+} and diode-pumped at 808 nm or 940/970 nm, respectively. Solid state lasers have some significant advantages over other candidates in their simplicity of operation, size, the possibility to generate multi-wavelength source by non-linear optical devices, and the absence of toxic gases which provides simple logistics and handling.

Owing to their relatively compact size, solid state lasers are highly mobile, and can be integrated on land or air platforms. On the other hand, SSL is a short-range tactical laser weapon, and like the COIL, it is limited by atmospheric transmission and weather conditions, and its wavelength reflection from the target is higher compared with longer-wavelength gas lasers. Solid state lasers are in the development phase with the following challenges: reduce the size, increase pumping efficiency and output power, heat removal from the crystal and diodes. There are several types of solid state lasers which are currently being developed:

3.1. Diode-pumped solid state crystalline lasers

Developed under Joint High Power Solid State Lasers (JHPSSL), by Northrop–Grumman this laser produced 105 kW output power at 2 diffraction-limited beam quality. The 100 kW laser is a combined slab MOPA, where seven of 15 kW laser chain slabs are phase locked. Each chain is actually a combination of a 200-W Yb-doped fiber amplifier (YDFA), and a series of four end-pumped, gain module-slabs, with a total amplified output power of 15 kW. The amplifying chains are arranged in parallel, and are driven by the same oscillator. Fig. 2 presents a view of one of such four end-pumped gain module slabs of the amplifying chain.

Fig. 1. Boeing 747–400F with the COIL airborne laser that is capable to destroy ballistic missiles at their boost-phase. The nose-mounted turret is the laser beam exit (Courtesy of Northrop–Grumman.).

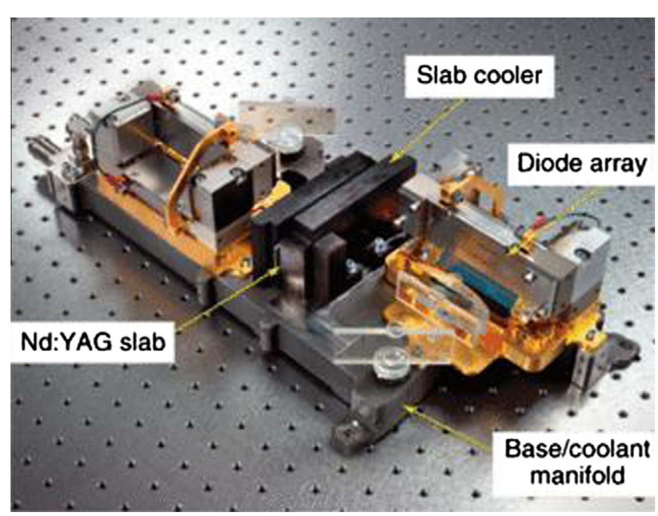

Fig. 2. A gain module slab which is a part of the amplifying chain developed by Northrop–Grumman, with a total amplified output power of 15 kW (Courtesy of Northrop–Grumman.).

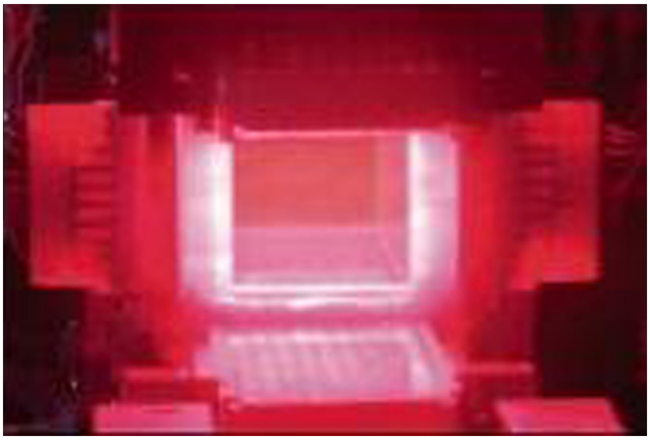

Fig. 3. A cross-sectional view of the $10 \times 10\,cm^2$ diode-pumped, heat capacity, Nd:YAG ceramic slab laser developed at LLNL (Courtesy of Lawrence Livermore National Laboratory.).

Each amplified beam is wavefront-corrected, and all the seven amplified beams are combined to form a single-aperture coherent beam. A two-chain laser produced 30-kW output power with 2.1 times diffraction limited beam quality, 20% optical efficiency, and several-minutes operation.

Another approach, developed by Textron is the "ThinZag" configuration, which utilizes Nd:YAG ceramic slabs, placed between pieces of quartz, tilted at such an angle that allows total internal reflection of the laser beam passing through the slabs. It produced by 2007 15 kW, and recently – 50 kW using two ceramic slabs in series. This zigzag motion compensates for variations in the off-axial refractive index, improving significantly the laser beam quality. The ceramic material allows scale of power by increasing the gain medium size instead of adding lasers, thus circumventing challenges of homogeneous and distortion-free beam combiners.

3.2. Heat capacity lasers

This solid state pulsed laser, is being developed at the Lawrence Livermore National Laboratory (LLNL). It is a large aperture ($100\,cm^2$) Yb or Nd:YAG ceramic slab, unstable resonator, wavefront-corrected laser beam. The laser medium is not actively cooled during the pulsed bursts operation which means that thermal gradients in the laser rod are minimized by keeping thermal load on the laser during operation [3]. After each burst the laser is turned off to cool. Therefore, mechanical and thermo-optical stresses inside the crystal are significantly reduced [4]. This laser produced in 2007, 67-kW average output power at 20% duty cycle, for a short time, and with 2–3 times diffraction limited beam quality. Fig. 3 presents a cross section view of one end of the diode-pumped Nd:YAG ceramics SSL developed at LLNL.

3.3. Disk laser

The disk laser is a face-cooled laser medium with high ratio of surface to volume, and multi-pass pump configuration via several HR parabolic mirrors. The axial heat flow coincides with the laser beam direction, and therefore eliminates the radial temperature gradients and thermal lensing effects. Scaling of a single-disk output power (≈5-kW) can be achieved by increase the number of pump modules or by using a multiple-disk configuration in series. Boeing Directed Energy Systems produced a thin disk diode-pumped Yb:YAG laser operated at power levels of >25 kW, 70% efficiency, suppressed radial ASE, with a nearly-diffraction limited beam quality and operated for several seconds [5]. The laser system is a series of Trumpf Inc. commercial lasers used in automotive industry – see Fig. 4 for more details [6]. This laser is scalable to a 100-kW output power, using the same technology. This is supported by predictions that a 30-kW output power can be extracted from a single disk, and therefore a target of 100-kW with good beam quality is feasible.

3.4. Fiber lasers

Fiber lasers based on rare earth doped fiber are also potential candidates for laser weapons. Fiber lasers are efficient sources, with reduced thermal induced-effects owing to their relatively large area per unit volume. The laser is a master oscillator power amplifier (MOPA) configuration. Companies like IPG [7] reported the operation of a 10-kW single-mode output power Yb^{3+} doped silicate fiber laser at 1 m, nearly diffraction limited beam, 500 m^2 effective mode area, and 90% optical efficiency with inner core diameter of 30 m, for a 10-kW unit. The fiber laser is an efficient source, compact, modular, expandable into a wide range of wavelengths with reduced thermo-optical effects, and no thermal degradation. The reduction in the thermal load is achieved by pumping at 1018 nm, close to the 1070 nm peak emission wavelength, with quantum defect of 5%. This robust laser can deliver through a *beam combiner*, up to 50 kW multimode output power through 100 or 200 m fiber with about four times diffraction

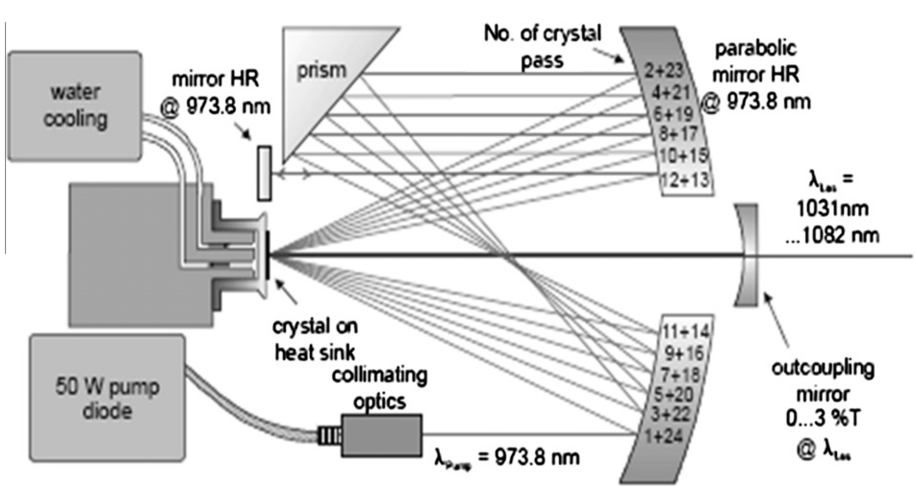

Fig. 4. A schematic layout of a commercial disk laser produced by Trumpf, Inc. (taken from Ref. [6]).

limited beam and-wall-plug efficiency higher than 30%. At present about 3 kW could be delivered to a target at about 1.2 km by NRL (USA) [8].

Disadvantages of fiber lasers such as optical nonlinearities (mainly above 5 kW), optical damage due to high power densities inside the fiber inner core, and dopant uniformity are still major issues to be considered in future upgrading of the fiber laser performance.

Finally, the shortfalls of both beam quality and laser efficiency can be reduced significantly by using cryogenically-cooled high power diode-pumped Yb:YAG lasers. The intrinsic advantages of Yb:YAG suggest that Yb-doped crystals are excellent candidates for high power lasers, with reduced thermal effects. Recent results of 963-W output power at 91.9 slope efficiency and beam quality of $M^2 < 1.3$ were reported recently [9].

4. Other lasers

It is worth only mentioning other laser candidates under currently development for military applications. One candidate is the Free Electron Laser (FEL) for the Navy, currently being developed under contract from the Office of Naval Research by Boeing and Raytheon. The FEL is an all electric *tunable* source over a large bandwidth. The Navy proposal is aimed at the development of a tunable 100-kW source and further to MW-class laser, that can intercept incoming missiles in a range of 2 km. Depending on the environmental conditions, the laser can be tuned on a day-to-day basis.

Other efforts are to develop efficient (60%), low divergence and reliable pumping sources for solid state lasers such as multi-kW conductively cooled laser diode stacks that are compatible with solid state laser technology, and ultrafast solid state lasers (high peak power in the fs time regime) to create induced plasma, local heating and ultrasonic shock waves – an effect known as dynamic pulse detonation (DPD). This is a non-lethal alternative in various scenarios such and applications such as border control, protection of sensitive facilities, law enforcement operation, protecting security checkpoints and the same. The very high peak power is accompanied with a very intense electromagnetic pulses as well as filamentation effects in the air towards the target, with the ability to stun, disorientate or paralyze target enemies. Last but not least is the space borne laser (SBL) designed in the 1980s for extreme range-targets, which is a part of ‘‘planetary defense system’’, based on high power HF chemical laser.

5. Conclusions

Lasers are going to revolutionize the battlefield by providing *ultrafast* and *ultra-precision* capabilities, with reduced collateral damage. They are divided into two types: gas lasers (chemical lasers) and solid state lasers (SSL). Lasers are considered both strategic weapon and tactical weapon, according to the laser type. Solid state lasers are compact, deployable systems with reduced logistics that can be used as a tactical weapon on the ground, on bombers or on strike fighters, mainly against short range rockets or missiles. They can also be used for ultra-precision missions with reduced collateral damage, both in the battlefield or in urban environment. The operation of SSL is limited by atmospheric distortion, high laser beam reflectivity from the target, clouds, and weather conditions. Scaling the output power requires advanced cooling architectures, novel laser materials, efficient, low-divergence multi-kW laser diodes, and effective beam-combining optics.

Ground based gas lasers such as the HF/DF chemical lasers are megawatt-class lasers. Chemical lasers operating around 100-kW are considered as a tactical weapon. These lasers are efficient (30%), technologically matured, with successful performance both as tactical, strategic weapon. Also, heat removal from the lasing medium is easier relatively to high power solid state lasers. The airborne version of this laser (ABL) has the capability intercepting and destroying missiles before the separation of warheads, at the boost phase, well above clouds. Recently Boeing Defense Space and Security, which is the main contractor of the ABL Testbed (ABLT) announced that for the first time, its airborne laser destroyed a ballistic missile in the boost phase. Although no other details were released, hitting and destroying an in-flight ballistic missile at the boost phase marks a significant success of the project.

The main drawbacks of a gas chemical laser are their large size, logistics, potential toxic and corrosive gases involved in the lasing process. Despite these limitations, the laser weapon has unique characteristics which make it a weapon of the ‘‘space age’’.

Acknowledgment

I would like to thank Dr. Boaz Lissak and Dr. Oded Amichai for their useful comments.

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